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COMMUNICATIONS IN SPACE OPERATIONS*

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<u>Lecture</u>	<u>Title and Author</u>	<u>Paper</u>
2	<u>The Space Environment</u> , by A. G. Wilson	P-1427
3	<u>Trajectory Fundamentals</u> , by S. Herrick	P-1303
4	<u>Types of Flights</u> , by R. W. Buchheim	P-1428
5	<u>Propulsion Fundamentals</u> , by B. Pinkel	P-1429
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10	<u>The Penetration of Planetary Atmospheres</u> , by	P-1322
13	<u>Orientation and Control</u> , by T. B. Garber	P-1430
14	<u>Some Information Theory Considerations in Space Communications</u> , by P. Swerling	P-1393
15	<u>Communication in Space Operations</u> , by C. M. Crain and R. T. Gabler	P-1324
16	<u>Internal Environment of Manned Space Vehicles</u> , by S. H. Dole	P-1309
17*	<u>A Discussion of Energy Sources for Space Communi- cations</u> , by J. H. Ruth	P-1318
19	<u>Space Flight Ground Facility Requirements Problems-- Launching Facilities</u> , by J. J. L'Sullivan	P-1431
20	<u>Scientific Exploration in the Fringe of Space</u> , by W. W. Kellogg	P-1350
21	<u>Physics of Solar-Terrestrial Space: Lunar Flight</u> , by E. H. Vestine	P-1344
22	<u>Interplanetary Exploration</u> , by A. G. Wilson	P-1432
23	<u>Some Elementary Facts of Relativity</u> , by H. A. Lang	P-1433
24	<u>Outer Space and International Law</u> , by Leon Lipson	P-1434
25	<u>Some Political Implications of the Space Age</u> , by J. M. Goldsen and Leon Lipson	P-1435

*The paper is based on unclassified portions of the lecture.

P-1394
2-24-58
111

<u>Lecture</u>	<u>Title and Author</u>	<u>Paper</u>
30	<u>Lunar Base Planning Considerations</u> , by R. D. Holbrook	P-1436
32	<u>Soviet Astronautics</u> , by F. J. Krieger	P-1437
34	<u>Food Preservation</u> , by J. H. Huth	P-1438

COMMUNICATION IN SPACE OPERATIONS

by

C. M. Crain
R. T. Gabler

earth-space vehicle → The value of space vehicles operating at great distances from the earth will be dependent to a high degree on the ability to communicate with these vehicles. The purpose of this paper is to explore the many practical factors involved in ~~the~~ communication problem, to indicate the factors which will influence most strongly the system designs, and to point out areas in which research and development appear needed. ↗

INTRODUCTION

The previous paper* on information theory has given us a good background on one of the basic theoretical limitations in the communication problem. In spite of the concrete answers that are apparently obtained from the simple formulas of information theory, it does not really solve design problems. It essentially establishes a limit or goal which can only be considered as the ultimate in the conservation of transmitter power.

In the design of communication equipment for space travel one will perhaps be compelled to make some unusual trades and design compromises which will result in odd designs and novel use of components. However, the means for attempting to meet communication requirements will be found in applying fundamental principles of communication to radically new conditions and environments.

*See P-1393 by P. Swerling.

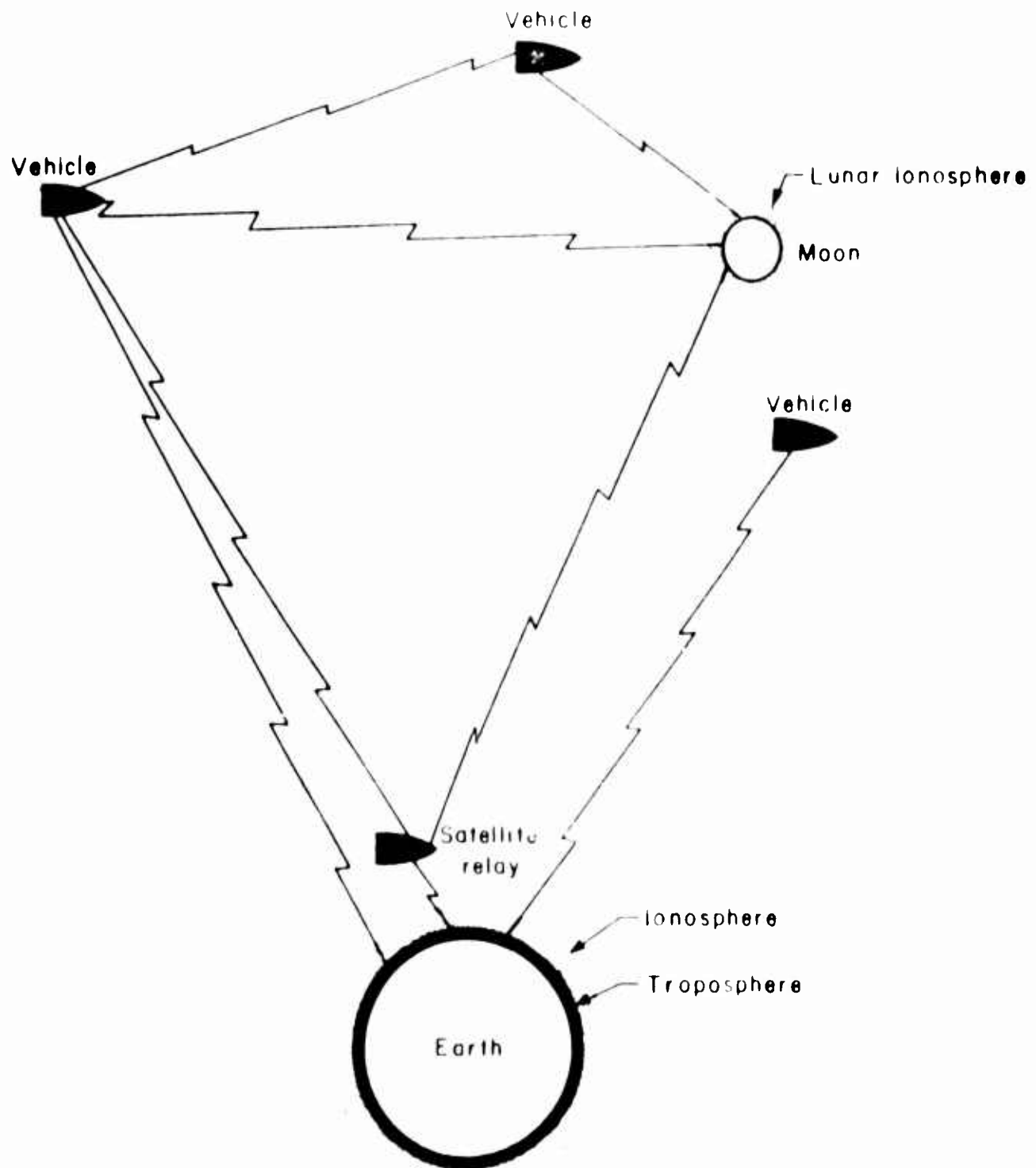


Fig.15-1—Possible space communication links

Figure 15-1 shows a sketch of potential communication requirements. The recent experiences with the meager links between the earth and various satellites will be most valuable in future developments.

GENERAL DESIGN CONSIDERATIONS FOR COMMUNICATION LINKS

The ratio of transmitted power to theoretical receiver noise in a radio communication link is given,⁽¹⁾ in decibels, by:

$$10 \log_{10} \frac{P_t}{P_n} = A_p + \frac{S}{N} + (nf) - G_t - G_r - (nif) + P_L + X \quad (15-1)$$

where

- P_t = transmitted power
- P_n = noise power in the receiver
- $\frac{S}{N}$ = required signal/noise ratio at receiver
- (nf) = noise figure of the receiver
- G_t = transmitter antenna gain
- G_r = receiver antenna gain
- (nif) = noise improvement factor
- A_p = path attenuation between isotropic radiators =
 $\log_{10} (4.56 \times 10^3 r^2 D^2)$
- P_L = propagation absorption loss
- X = polarization loss

The design problem consists of choosing such things as frequency, antenna gain, transmitter power, etc. in such a manner as to best* meet the requirements specified.

*In the sense of proper balance between system performance, cost, etc.

Since receiver noise figure, antenna gain, propagation loss, etc. are variables with frequency, one must first investigate these factors individually.

We first consider the case of a radio link with one terminal at the earth's surface. In the radio spectrum frequencies below at least 10 megacycles can be ruled out because of reflection effects of the earth's ionosphere, and frequencies above about 30,000 megacycles are generally unsuitable because of atmospheric attenuation by oxygen and water vapor. This relates to the factor P_L in Eq. (15-1). Thus, on the basis of propagation loss considerations alone, one can restrict the design to frequencies between about 10 and 30,000 megacycles if one end of the communication links is on the earth's surface. Other undesirable effects such as the rotation of the plane of polarization of waves traversing the ionosphere will further restrict the use of frequencies available unless special antennas (such as the use of circular polarization) are provided to accommodate polarization variations. If polarization rotation effects are to be made negligibly small, frequencies above at least 1000 megacycles must be used. (Polarization rotation is proportional to $1/f^2$ and the total electron content along the transmission path.) The 'peculiar' characteristics, i.e., the apparent low-frequency modulation on the signals from the Sputniks can be primarily accounted for by rotation of the plane of polarization of the waves in the ionosphere and the spin of the vehicle.

It should be pointed out here that if the communication link is between two vehicles, both of which are beyond the earth's ionosphere (see Fig. 15-1) the above discussion is not appropriate. As a matter of fact, the communication problem for these links will involve trade-off

considerations between directive vs non-directive antennas, antenna pointing vs apparatus necessary for control, low-frequency vs high-frequency sources and circuit components, and might in some cases indicate the use of frequencies much lower than permitted when one terminal of the link is on the earth's surface. In such systems a primary consideration in the design will be that of optimizing life for a given system performance level and system weight.

The path attenuation factor, A_p , as used in Eq. (15-1) is directly proportional to f^2 . (see Fig. 15-2). For an antenna of a given size, the antenna gain (G_t or G_R) is proportional also to the square of frequency (see Fig. 15-3). Thus, if both receiving and transmitting antennas are directive, for antennas of fixed size the higher the frequency of operation chosen the more the received power for a given transmitter power. The use of directive antennas on certain space vehicles will not be very practical due to the problems of keeping the beam directed toward the antenna on the earth's surface. The design tradeoff here is loss of system gain using a non-directive antenna versus the weight, energy consumption, and general control difficulties of orienting the antenna beam from the space vehicle always toward the earth or receiving antenna. The so-called omni-directional antenna seems by far the most likely approach at this time.

The noise improvement factor (nif) depends on the type of modulation employed. A general discussion of this term is beyond the scope of this paper. For amplitude modulation this term is zero (in db) and may be several db in the case of frequency modulation if adequate signal level is available, depending on the type of noise involved. For the purpose of this paper, neglecting this term has little effect on the conclusions reached.

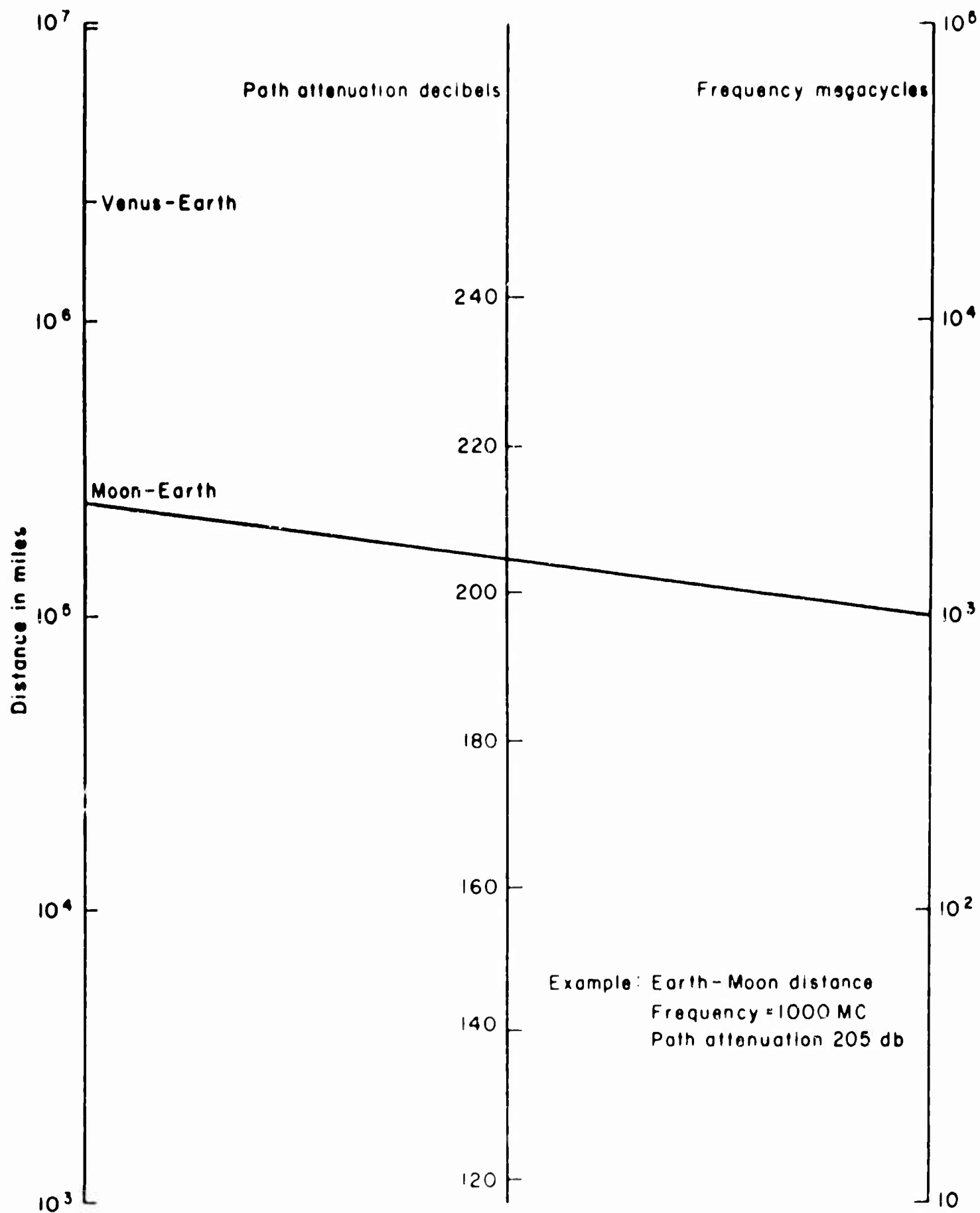


Fig.15-2—Path attenuation between isotropic antennas

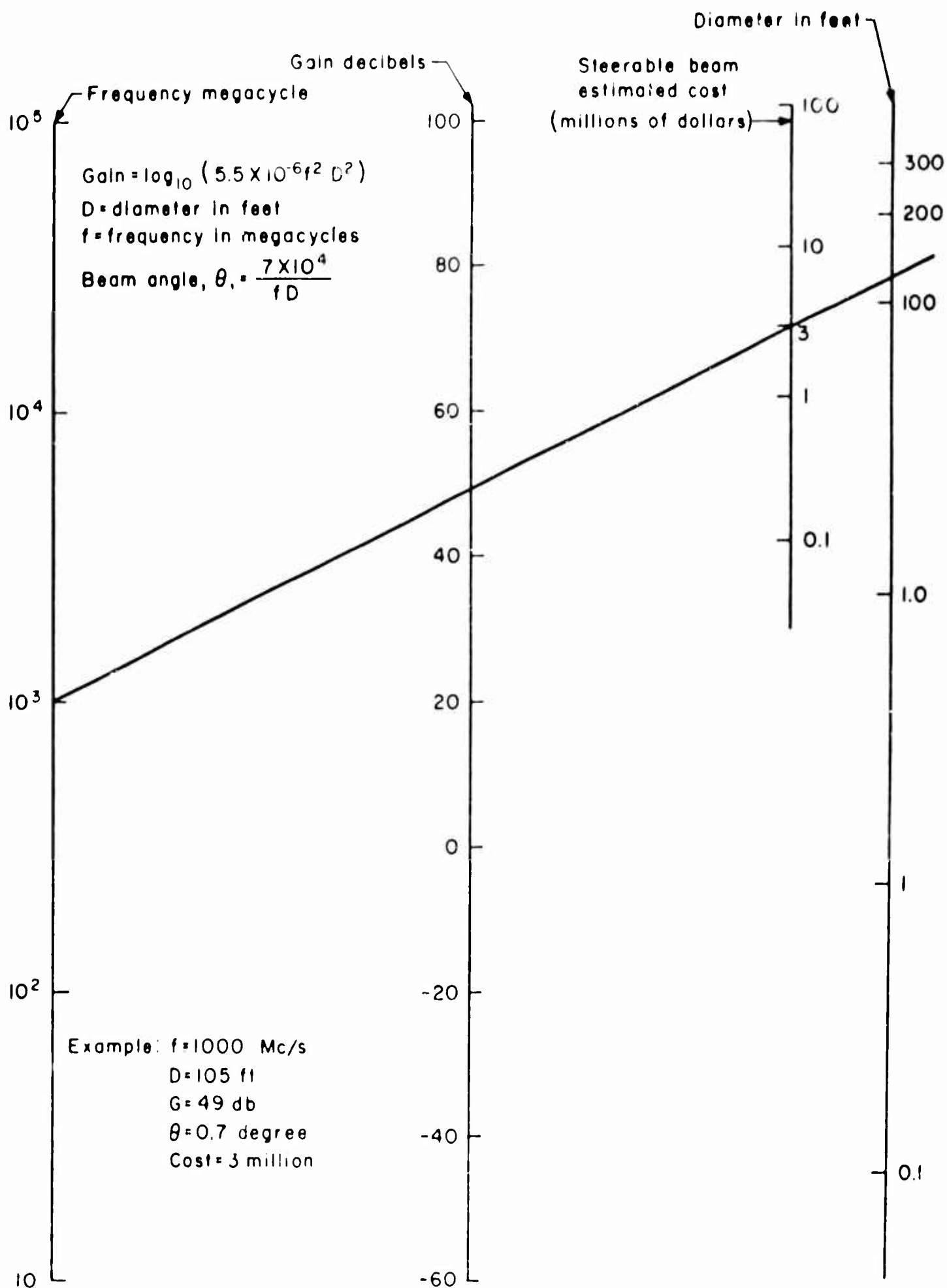


Fig.15-3—Relations between parabolic antenna gain, frequency, size, and estimated cost (steerable beam)

The term $\frac{S}{N}$, or desired signal-to-noise ratio, depends on the particular type of system under consideration. In some cases, a ratio of 10 or less is adequate and in others higher values are required. A television picture of average quality has a signal-to-noise ratio of the order of 100 (20 db), and speech is intelligible with signal-to-noise ratios of the order of 2 (3 db).

The noise figure of receivers is approximately proportional to frequency in the frequency range of 100 to 10,000 megacycles. At 300 megacycles noise figures of 2 to 4 have been obtained, while at 10,000 MC a value of 20 (or 13 db) is reasonable. Obviously, this indicates the choice of frequencies in the lower range, if possible.

Combining all the above considerations one can conclude that frequencies in the range of 300 to 3,000 MC appear somewhere near optimum for earth-to-space systems. At lower frequencies ionospheric effects are troublesome; at higher frequencies receiver noise may dominate; and at even higher frequencies atmospheric absorption is a limiting quantity.

There are new type detectors such as masers and cooled-crystal detectors on the development horizon which will greatly reduce the receiver noise problems at the higher frequencies in our range; however, overall improvement from using these elements will not be nearly as much as a comparison of detector noise figures would indicate, since cosmic noise, solar noise,* and man-made noise will impose limitations at a level not very far

*The normal levels of the emissions from these sources are quite frequency-dependent, with the intensity decreasing with increasing frequency. In the frequency range under discussion the levels are such that, in general, for non-directional antennas cosmic noise predominates and, with narrow beam antennas directed at sources such as the sun or radio stars, solar or astral noise predominates. The strongest radio star, Cassiopeia, produces a flux density of about 2×10^{-22} watts per square meter per cycle bandwidth at the earth, at a frequency of 100 MC. This is approximately the same as that produced by a quiet sun.

below that now resulting from receiver detector noise. These new devices will be much more attractive for radio astronomy applications where the object is to detect such things as cosmic and radio star emissions. In space communication considerations, those emissions are naturally undesirable interference or simply another type of noise.

DESIGN EXAMPLE: VOICE AND VIDEO LUNAR LINKS

Let us apply our conclusions to the problem of designing a voice transmission circuit between the earth and a space vehicle near the moon. We will arbitrarily assume a bandwidth of 1000 cycles at a 1000 megacycle center frequency, and assume the necessity of a signal-to-noise ratio of 10 db. Also, we will neglect the noise improvement factor in the analysis, since it will depend on specifying a particular type of modulation.

At a frequency of 1000 megacycles, the propagation loss due to energy absorption in the medium should be in the fractional db range, or negligible for the earth-moon path. The path attenuation loss, A_p , involves the divergence of energy with distance from a point source and amounts to 205 db at 1000 MC.

The receiver noise power is evaluated from the theoretical thermal noise expression

$$P_n = 4 \times 10^{-21} \times \text{receiver bandwidth.} \quad (15-2)$$

For our case, we have assumed that a bandwidth of 1000 cycles is adequate for voice transmission. Thus

$$P_n = 4 \times 10^{-21} \times 1000 = 4 \times 10^{-18} \text{ watts} \quad (15-3)$$

Noise figure (nf) of the 1000-megacycle receiver will be close to 8 db if we assume the use of present type equipment. The question now arises as to the noise power radiated from the moon itself. If we point an antenna at the moon, how much noise is received relative to cosmic noise? Some data available on such problems as this indicate noise temperatures up to several hundred degrees Kelvin in the microwave region. The need for more data of this type is indicated; however, for our particular design, such noise is not a limiting quantity.

Summarizing our design we have

$$\begin{aligned} \frac{S}{N} &= 10 \\ P_n &= 4 \times 10^{-18} \\ (nf) &= 8 \text{ db} \\ (nif) &= 0 \text{ by assumption} \\ P_L &= 0 \text{ (due to proper choice of frequency)} \\ A_p &= 205 \text{ db from chart (Fig. 15-2)} \\ G_t &= 0 \text{ (isotropic transmitting antenna in the space vehicle)} \end{aligned}$$

or

$$\begin{aligned} 10 \log \frac{P_t}{4 \times 10^{-18}} &= 205 + 10 + 8 - 0 - G_R - 0 - 0 \quad (15-4) \\ &= 223 - G_R \end{aligned}$$

Thus, we can choose arbitrarily the space vehicle transmitted power and the earth-based antenna gain to satisfy the above equality. Making P_t large is undesirable because of the energy consumption factor for the space vehicle, and making G_R large is undesirable because of mechanical problems in positioning, difficulties in tracking with very narrow beams, cost, etc.

If we assume $P_t = 1$ watt, we can calculate immediately that

$$G_R = 223 - 174 = 49 \text{ db.}$$

A 49 db gain parabola operating at 1000 mc/s has a nominal diameter of 105 feet as shown in Fig. 15-3. The beam width of such an antenna is 0.7 degree. A steerable parabolic dish of this size will cost several million dollars, and the cost increases⁽²⁾ exponentially as the size increases.

If we decrease P_t to, say, 0.1 watt, the corresponding antenna diameter and beam angle are 350 feet and 0.2 degree. The beam from this antenna would cover only two parts per million of the hemisphere. Due to practical problems such as refraction and scintillations in the angle of arrival of radio waves in traversing the atmosphere, satisfactory system performance with such an antenna may prove most difficult. If the transmitter's position in space were exactly known the acquisition and tracking problem would be bad enough; if the position were unknown, the problem of acquisition and continuous tracking would appear most formidable even with the use of advanced and complex searching techniques. It would appear that for this example, the use of transmitted powers of a watt or more would be a practical requirement.

If we wish to transmit live pictures from the vicinity of the moon using television equipment* of somewhere near the present broadcast quality we can calculate by the above procedure the system requirements. If we assume the transmission is at a frequency of 1000 megacycles as before, we obtain for a 4 megacycle bandwidth and a signal-to-noise ratio of 10 db,

$$10 \log_{10} \frac{P_t}{1.6 \times 10^{-14}} = 223 - G_R \quad (15-5)$$

*An alternate method of picture transmission will involve photography, film, and a film scanner. The TV system requirements are not nearly as elaborate, as the scanning can proceed at an arbitrarily slower rate. A complete comparison of the advantages and disadvantages of these systems will not be undertaken here.

Assuming the 105-foot, or 49 db, parabola on the earth (as used in the audio link), we obtain

$$10 \log_{10} \frac{P_t}{1.6 \times 10^{-14}} = 174$$

or

$$P_t = 2.5 \times 10^{17} \times 1.6 \times 10^{-14} = 4000 \text{ watts}$$

DOPPLER EFFECTS

An additional factor which can complicate our problem is that of doppler shift. Let us imagine using a simple system in which we transmit a stable frequency, say 1000 megacycles from the earth or space vehicle antenna with a 1000 cycle system bandwidth, as in our audio link example. The received frequency is different from the transmitted frequency by the amount of the doppler shift (due to the relative velocity between the transmitter and receiver). This shift is given by the relation

$$f_D = \frac{f_{\text{transmitted}} v/c}{\sqrt{1 - \left(\frac{v}{c}\right)^2}}$$

where

f_D is the doppler shift

v is the relative velocity between transmitter and receiver

c is the velocity of light

If we assume that the relative velocity is small enough to ignore relativity effects, the relation becomes

$$f_D = f_{\text{transmitted}} v/c$$

For

$$v = 15,000 \text{ meters/sec and } f(\text{transmitter}) = 1000 \text{ megacycles}$$

$$f_D = \frac{10^9 \times 1.5 \times 10^4}{3 \times 10^8} = 5 \times 10^4 \text{ or } 50 \text{ KC.}$$

Thus, the received signal frequency is 50 kilocycles different from the transmitted frequency. If we are attempting with our narrow-beam antenna and narrow-band sensitive receiver to receive the space vehicle transmissions and do not know the frequency we are attempting to receive, we obviously have severe acquisition problems. This problem can be alleviated on the ground end of the link by using more complex receiving equipment (for example, many separate narrow-band receivers). However, this procedure does not appear attractive for the space vehicle installation when we think of the weight, volume, and electrical energy consumption factors involved. We will not pursue further possible solutions to this problem in this limited discussion.

ELECTRICAL ENERGY FACTORS

In current communication links one is normally concerned primarily with power considerations. For space communication links total energy consumption will probably be a more important factor than power consumption alone. One will be interested not only in the system requirements for a given task but also in the life of the link.* If electrical energy is to be supplied from stored energy of some form in the space vehicle itself one can arrive at a reasonable life estimate from the simple relation

*The relatively short radio communication life of the recent satellites is a pertinent example.

$$\text{Life} = \frac{\text{watt-hours per pound of energy source} \times \text{pounds of energy source}}{\text{total power consumption of communication system}}$$

For example, the 1-watt transmitter in our previous example would consume a total of perhaps 10 watts, when auxiliary system components, filament power, amplifier efficiency, etc., are considered.

Practical energy sources can deliver,* say, 50 watt-hours per pound. Thus, the voice transmitter for the lunar link would have some five hours of life per pound of electrical energy source. The video transmitter (4000 watts radiated power) would have a total power consumption of perhaps 10,000 watts. Thus, it would require 10,000/50 or 200 pounds of electrical energy source for each hour of transmission.

(In the above examples, the assumption is made that the acquisition, tracking, doppler shift, and other problems have been solved so that the system actually performs as advertised.)

The use of devices such as currently available solar cells appears quite attractive for space communication applications, since the energy is supplied by an external source instead of being carried in the space vehicle. Solar radiation amounts to about 2 KW per square meter in outer space and can be converted to electrical energy in presently available silicon cells with about 10 per cent efficiency. The performance of these devices under the influence of meteor and cosmic bombardment is yet to be ascertained.

The use of nuclear sources for electrical energy appears feasible, particularly for large energy-consuming systems; however, the use of such sources in the vicinity of transistors and other components of communication systems may involve special considerations in shielding, etc.

*See P-1318 by J. H. Huth.

SUMMARY

In this paper, we have attempted to present a somewhat general picture of the nature of the space communication problem and have slanted the discussion toward systems in which one end of the link is on the earth's surface. Specific examples of an audio link and a video link to a lunar distance were presented to indicate somewhat specifically how various factors affect the overall communication problem. It would appear that the problem of satisfactory communication with space vehicles at lunar distances or beyond may be quite difficult (depending on the weight limitations) and will also be quite expensive even if the rate of information transmission is quite small relative to current standards.

Areas of research and development (other than building larger and larger payload vehicles) which appear most important to achieving various practical communication systems for space operation include:

- o Radiation characteristics, both thermal and non-thermal, of the various extra-terrestrial sources such as the sun, moon, planets, radio stars, and the galaxy.
- o Design and performance of large antennas with steerable beams.
- o Antennas for space vehicles.
- o Sources of electrical energy for space vehicles and their operational characteristics in a space environment.
- o The effect of the earth's troposphere and ionosphere on the transmission of radio waves of various frequencies.
- o System components such as transistors, tubes, and low noise detectors.

- o Best methods of acquisition and tracking of sources having low intensity and variable frequency emission.
- o The composition of space outside the earth's atmosphere, including the solar and lunar atmosphere.
- o Methods of encoding information for most efficient transmission.
- o Means of obtaining reliability for unattended operation in space environment.

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1. Reference Data for Radio Engineers, Fourth Edition, 1956.
2. Kraus, Proc. I.R.E., Vol. 46, No. 1, 1958, p. 92.